The different approach for supercapacitor modelling in the perspective of self-discharge study

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ABSTRACT

Supercapacitor is a relatively new type of electric component used to store energy compared to a battery. Supercapacitor charge and discharge cycle are faster compared to the battery along with higher power density which increase its application in recent years. However, supercapacitors have quite high self-discharge compared to batteries. This makes energy stored in supercapacitor decrease faster over time when not in use. Various study has been done towards the self-discharge behavior of supercapacitor (SC) which is both experimentally and in simulation. The simulation is done by various methods and models which have been proposed by previous researchers. Most of the methods that have been used were based on the equivalent circuit model (ECM) as it is the easiest method available. However, there is still another method proposed such as the Fractional-order model. This paper will review some of the methods and models used to study self-discharge behavior.

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1. INTRODUCTION

The demand for energy storage increases over time along with the demand for renewable energy system and electric vehicles which both requires energy storage to store the energy and released the energy when required [1]. There are numerous types of energy storage that have been used now such as battery, supercapacitor and fuel cells [1], [2]. Supercapacitor (SC) is one of the energy storage types other than the battery. It stores energy in terms of electrostatic. Supercapacitor has been studied and used in electric vehicles, energy storage for photovoltaic systems such as solar panels and other electrical applications such as regenerative braking of the elevator [3]–[7]. In photovoltaic application, supercapacitor is suitable to be implement as a backup power in short term of time and as to stabilize the grid [8]. The usage of 5 SC in the photovoltaic system able to increases the energy self-consumption and energy self-sufficiency of the system [9]. The hybrid energy storage also has been proposed by researchers to improve the energy storage system [10]. The supercapacitor is coupled up with battery as hybrid energy storage system (HESS) in electric vehicles which will provide the excess energy needed whenever battery cannot provide during high power demand [11], [12]. The same reason applied in [13] in the algaculture machinery application which relied on photovoltaic as the main source and HESS as the energy storage. Supercapacitor also used as virtual inertia support for wind turbine where it helps to reduce frequency nadir and also avoid the unwanted frequency dip when in the recovery process [14].

Supercapacitor is divided into three categories which are the electric double layer capacitors (EDLC), the Pseudocapacitor and the combination of both called Hybrid capacitors [15]. The difference between the three categories is their electrode material. The EDLC used a carbon-based material for both electrodes of the supercapacitor [16]. While Pseudocapacitor used conducting polymer or transitions of metal oxides as the electrode [17], [18]. The power density of a Supercapacitor is greater compared to the battery which makes it perfect use for higher power applications. The supercapacitor is also able to charge up more rapid and discharge faster [19]. Despite the fast-charging and discharging cycle, a supercapacitor lifespan could achieve hundred thousand of cycles before it becomes inefficient or obsolete [20]. Fast charging has become one of the major concern such as in the automobile industry as the lithium-ion battery strictly need to be charged below its charging rate, C to avoid any damage happen to the battery [21]. This makes supercapacitor has upper hand advantages as it can absorb higher current instantly during charging phase and will not damage the supercapacitor as much as the battery will [21], [22].

Supercapacitor and battery have their own leakage current or self-discharge condition. However, the self-discharge of supercapacitor is greater than battery [23]. Self-discharge or also called the voltage drop of the supercapacitor happen during open-circuit condition or when they are not in use and stored for a certain amount of time. The high free energy state at the early windows makes the voltage decrease gradually. The mechanism of self-discharge can be grouped into ohmic leakage, charge redistribution and faradaic reactions. Self-discharge is affected by the charge redistribution which is also affected by the charging current either high or low along with the duration of the charging and charging method. As in [21], different constant current applied to charge the same capacitance of SC and shows different self-discharge behavior. Temperature also gives effect towards supercapacitor's self-discharge where the supercapacitor is stored [23]. In electrochemical studies, the diameter of the electrode also affected the self-discharge of a supercapacitor where a higher diameter shows a higher rate of self-discharge [24]. Various factors affecting the self-discharge make it inevitable which then lead to various study on self-discharge behavior. An accurate model is important so that it can imitate the supercapacitor's self-discharge behavior for real-life applications. As the self-discharge affect the supercapacitor, it needs to be studied thoroughly so the efficiency of a supercapacitor can be maximized before implement into any application.

This paper will review the self-discharge study based on different approach such as the equivalent circuit model (ECM), mathematical model and some experimental studies done by previous researchers. In section 2, the ECM will be reviewed and then followed by Fractional order model and experimental measurement approach in section 3 and section 4, respectively. Then all the reviewed paper and method will be discussed on their advantages and disadvantages towards the self-discharge study in section 5 for future use and improvement toward the proposed method for better study.

2. EQUIVALENT CIRCUIT MODEL

Equivalent circuits are often used to model supercapacitors [25]. The (ECM) of supercapacitor is also used to determine and study the characteristic of supercapacitor which is crucial to predict the behavior before being applied to any application. The circuit consists of the basic electrical component which is the resistor and capacitor which either can exist as a single component or multiple components and also can be either connected in series or parallel [26]. There is various type of proposed ECM of supercapacitor which is the classical model, resistor-capacitor (RC) branch ECM which is two branch ECM and three branch ECM, ladder ECM, transmission line model, multi branch model and dynamic model [25], [27]–[30]. However, parameter identification still needs the help of experimental data. The most common used ECM for self-discharge behavior study is based on the two branch ECM and three branch ECM.

2.1. Three branch equivalent circuit model

The three branch ECM consisted of three RC branches parallel with each other and have their own time constant [31]. The three branch ECM was proposed by Luis Zubieta in 2000 and this model is also called Zubieta's model [28], [30], [32]. The model also paralleled with a resistance which represents the leakage resistance for the self-discharge study. Figure 1 shows the three branch ECM of Zubieta's model for the supercapacitor where the first RC branch on the left displayed the immediate branch where it happened immediately during charging and within seconds. The second branch is the delayed branch which that happens between seconds and immediately after the charging source is disconnected from the supercapacitor where the charge redistribution takes place. The third RC branch is also known as the long-term branch shows the behavior of the supercapacitor when the time is longer than 10 minutes [28], [33]. The resistance, R_L is the leakage resistance for this model. The simulation for this model is done by obtaining all the parameters which is the resistance and capacitance value for each branch through formulation based on the circuit model itself. The formula required value from the terminal voltage and time which is taken through an experiment done on the supercapacitor.

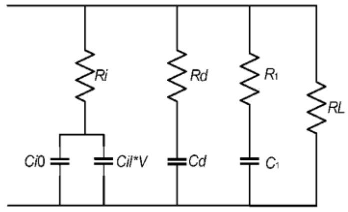

Figure 1. Zubieta's three branch ECM for SC [34]

Figure 1 shows the Three Branch ECM of Zubieta's Model for the supercapacitor where the first RC branch on the left displayed the immediate branch where it happened immediately during charging and within seconds. The second branch is the delayed branch which that happens between seconds and immediately after the charging source is disconnected from the supercapacitor where the charge redistribution takes place. The third RC branch is also known as the Long-term branch shows the behavior of the supercapacitor when the time is longer than 10 minutes [28], [33]. The resistance, R_L is the leakage resistance for this model. Parameter can be obtained by calculation for each branch. The example for parameter identification can be seen in [31], [33], [35].

The self-discharge behavior is non-linear at the early start of the self-discharge phase. However, it will start to become linear after a long time the supercapacitor in the self-discharge state as seen in Figure 2. In [27], self-discharge study was made and the simulation was done by the implementation of three branch ECM. The parameter extraction is done based on Maxwell BCAP350 350F supercapacitor where the SC is charged and let discharge in an open circuit condition using CH760E electrochemical workstation. The parameter is then tested with Faranda's model and optimized by using MATLAB/Simulink optimization tool to create the behavior fit to the experiment's result. The non-linear behavior can be seen happen when large voltage drops at the early moment of the phase. The high self-discharge rate happens due to the charge redistribution and moving electrons between the electrode.

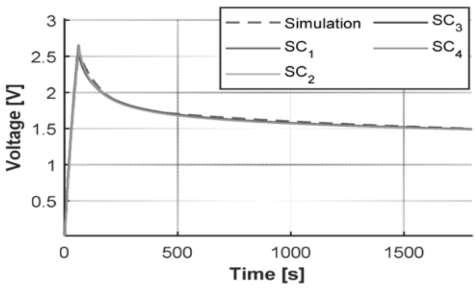

Figure 2. Self-discharge behavior for 4 unit of 100 F SC compared to simulation result [31]

A clearer self-discharge behavior waveform of a supercapacitor can be seen in [31] where the author used a lower capacitance value of SC for the study. The three branch ECM is used to study the SC characterization for automotive application. Four unit of Vinatech 2.7 V, 100 F SC voltage drop during self-discharge phase of each SC is physically measured to show the behavior and compared with the simulation study. The average parameter was obtained from the datasheet and experimental studies done by charging each of the SC with constant current and discharge it by let the SC in an open circuit for half an hour. The SC terminal voltage and its current is recorded by using NI9215 analogue data acquisition board. Then, the author used the same parameter identification method to simulate the self-discharge behavior of 24 units of supercapacitor in series connection (SC Bank) with the nominal capacitance of 4.17 F. Both experimental data and simulation are compared and the error trend is calculated by using (1).

$$Err(t) = v_{sc}(t) - v_{sim}(t), \quad (1)$$

The results obtain in [31] from measuring the SC bank self-discharge voltage was compared with the simulation which is based on Three Branch ECM where it shows that the model can imitate the real-life self-discharge nonlinear behavior of the SC. The model used and proposed also abled to create a low mean error at 0.372 V.

Zubieta's model is also used for the evaluation of the supercapacitor for the energy storage systems for photovoltaic modelling [33]. The 470 F supercapacitor is charged with 30 A before it is let to rest after charging for 30 minutes to see the voltage drop during self-discharge state. The parameter is obtained by measuring the terminal voltage in function of time while charging with constant current and by simple equation dedicated for each branch. The self-discharge of the supercapacitor start during the long rest phase is due to the movement of ions and the dipole's orientation that take a long time. The self-discharge also shows the charge redistribution process. Results in the studies also shows the same nonlinear behavior during the self-discharge phase. The margin error for both simulation and experiment results for the study is not exceeded 2%.

The parameter for the three branch ECM is obtained through calculation and help from experimental data such as the terminal voltage at a certain time. The obtained parameter is then used in the simulation to generate the self-discharge behavior of the supercapacitor as done by the researchers in [35]. In the study, the 470 F SC was charged up to its rated 2.7 V voltage with 27 A constant current and the terminal voltage is measured for parameter extraction and to compared with the simulation's result. The researcher proposed a new simple method to reduce the burden for computation of parameter identification for the Three Branch ECM and compared the simulation results with parameter identification proposed by Zubieta to validate the method proposed which is later able to show the same waveform for charging and self-discharge of supercapacitor. Most of the reviewed proposed method for three branch ECM use their own method for parameter identification but some used the method proposed before but with a different capacitance value of supercapacitor to validate that the method is universal. Some of the study also include parameter optimization technique to increase the accuracy. However, the simulation might differ between studies as some might use MATLAB and some might use PSIM to generate the simulation. Yet, all study still based on the three branch ECM.

2.2. Two branch equivalent circuit model

The two branch ECM of a supercapacitor is the same as the three branch ECM however without the presence of the long-term branch or the third branch. It consists of the immediate branch and the delayed branch to represent the supercapacitor behavior. The first branch is the charging phase while the second branch is to represent the charge redistribution process for the supercapacitor [36]. The self-discharge current, i_{sd} based on Ohm's Law can be denoted as in (2).

$$i_{sd}(t) = \frac{\Delta u(t)}{ESR} = \frac{-u_{sc}(t)+u(t)}{ESR}, \tag{2}$$

Where the $u_{sc}(t)$ is the supercapacitor voltage at open circuit and $u(t)$ is the real time SC terminal voltage.

The parameter identifications also need helps from the experimental data and some researcher uses a more complex calculation approach that needs helps from tools such as the least square method algorithm. The two branch ECM in Figure 3 has been used for characterization and behavior study for the supercapacitor in [37]–[40] while Figure 4 also shows the two branch ECM that has been used in [33], [36], [41] for modelling the supercapacitor behavior. The high self-discharge rate of a SC also can happen due to overcharged since the electrolyte might be decomposed into a gaseous state or solid product [42]. Ghanbari *et al.* [40] proposed an optimal time-domain approach for self-discharge study of supercapacitor based on the Two Branch ECM. A total of 59 sets of data were measured during the 6 hours of the self-discharging phase of the 22 F supercapacitor. All the data then being used to estimate the time domain of the terminal voltage for the supercapacitor with the help of the weighted least-square technique then the exponential function model is proposed. There is a total of 11 Exponential function models obtained then used to compare with the experimental data. The obtained 11 function is all straight line with small data. The combine 11 function shows that the result done by Ghanbari *et al.* [40] able to shows the nonlinear self-discharge characteristic of the 22 F SC used in the study. Next, the same parameter identified used to shows the behavior of the supercapacitor during the self-discharge phase and compared to the experiment measurement. The proposed method which uses the two branch ECM model along with the exponential function from the study in [40] able to increase the accuracy by 8.2%. However, the proposed method consists slightly more complex computation for obtaining the simulation results.

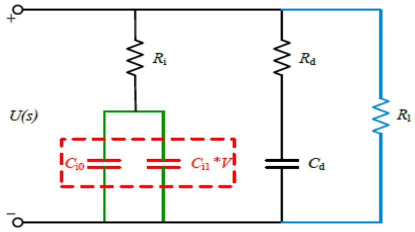

Figure 3. Two branch ECM for SC [43]

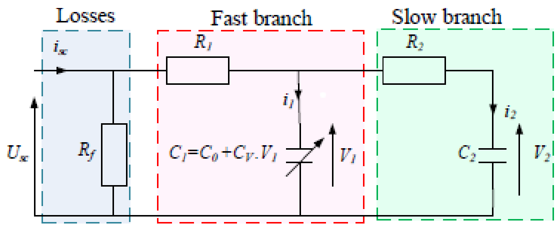

Figure 4. Two branch ECM with different resistor placement [29]

A supercapacitor rated voltage is between 2.7 to 3.0 V depending on the model and manufacturer. For the application that required higher voltage, a series of supercapacitors can be used to increase the voltage of the supercapacitor. Zhao *et al*. [38], explained a parameter identification method for the module of the supercapacitor is proposed by the researchers based on segmentation optimization (SO) to reduce the error for self-discharge identification compared to the recursive least square (RLS) method, especially during static conditions as there is no charging or discharging occurring at the moment. The parameter can be extracted through the Matlab/Simulink. The circuit analysis method for parameter identification of two branch ECM alone is imprecise to identify the Maxwell BCAP350 350F supercapacitor behavior during the stationary phase. The SO method proposed for parameter identification for the two branch ECM shows better accuracy with an error of 0.68% lower compared to the RLS parameter identification optimization method.

The two branch ECM is also being improved by adding a controlled current source (CCS) paralleled to the first branch which reflects the behavior of the supercapacitor during the self-discharge process which was done by Xu *et al.* in [37] for the SC behavior study. However, it cannot show the perfect correlation between the terminal voltage during the self-discharge with the change rate if it’s applied to dynamic SC model [44]. Hence, the CCS circuit was proposed to two branch ECM. The proposed circuit also can reflect the internal charge diffusion behavior. The parameter for the proposed CCS model is identified by using the help of the RLS algorithm. However, the data obtained from RLS needed to be optimized with an iterative optimization algorithm as it shows a large fluctuation toward the terminal voltage of the model. The optimized parameter can reduce the error to less than 1% and better nonlinear behavior characteristic of the SC.

3. FRACTIONAL ORDER MODEL

The fractional-order model is the implementation of fractional calculus that is applied to the circuit theory of the supercapacitor [45]. A fractional-order model is used to estimate the parameters of supercapacitors using data obtained from experiment and operating conditions [46]. The parameter required to be identified using fractional-order is fewer compared to the traditional RC ladder model and has a better efficiency in capturing the dynamic behavior of the supercapacitor [47], [48]. Various fractional order model for the SC behavior has been proposed in previous studies which were reviewed in [49] for the energy management strategies. Fractional calculus used in fractional order has wide applicability for modelling as it used derivative and integral operations in its operation. In (3) shows the fractional linear time-invariant (FLTI) equation.

$$\int_{n=0}^{N} a_n D_n^{\alpha}\, y(t) = \int_{m=0}^{M} b_m\, D_m^{\alpha} x(t), when\ a_n < a_n + 1 \tag{3}$$

D is the mean of the derivative and a_n (n = 0, 1, 2, ...) are the order of derivative that is assumed be a real number and positive value.

The concept of the complex number is applied in the modelling in which both polar and rectangular form is almost equal to each other. With detailed calculation done by researchers as in [50], the fractional-order model is then compared with the actual simulation from a simple capacitor model. The parameters extraction was done through two types of mathematical modelling for the self-discharge supercapacitor which is based on the characteristic of a regular capacitor and the other one is based on constant phase element (CPE). The self-discharge voltage, $V_{sc}(t)$ for both models can be seen in (4) for the regular capacitor model and (5) for CPE.

$$V_{sc}(t) = V_o * exp - \left[\frac{t-t_o}{R_p C}\right]^{1-n}, \quad (4)$$

$$V_{sc}(t) = V_o + I_c\left(\frac{t^{1-\gamma}-(t-t_{cutoff})^{1-\gamma}}{C(2-\gamma)!}\right) \quad (5)$$

where, V_o is the maximum voltage after the charging process, charging time, t_o and self-discharge time, t. R_p is the leakage resistance and C is the maximum capacitance of the SC and I_c is the charging current.

The fractional order model proposed in [50] able to shows an accurate correlation to the actual simulation done by using a potentiostat. The results may have few errors as can be seen in the study as it not 100% overlap between each the actual and mathematical model. However, it shows the capability of the fractional-order model proposed to display the behavior of supercapacitor which is nonlinear behavior for two different SC which is 4.7 F and 10 F.

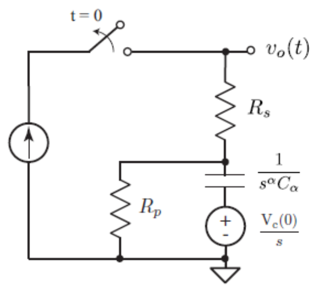

Figure 5. Fractional order model of a supercapacitor for discharging phase [51]

Figure 5 shows the fractional order model for a supercapacitor during the self-discharge phase where value α is given by the Caputo derivative as in [51]. This model is widely used in behavior estimation study for SC. The series resistor and constant phase element (CPE) are used in the fractional-order model to shows the supercapacitor behavior at low frequency. The output voltage terminal of the supercapacitor during the self-discharge process for model in Figure 5 is denoted as:

$$v_o(t) = V_c(0)E_{\alpha,1}\left(-\left(\frac{t}{\tau}\right)^{\alpha}\right), \quad (6)$$

where, $\tau = (R_p C_\alpha)^{\frac{1}{\alpha}}$, $V_c(0)$ is the voltage at time t=0 which is when the supply is disconnected from the SC. While the $E_{\alpha,\beta}(.)$ is the Mittag-Leffler function applied to the equation. The results obtained for the simulation based on the fractional-order model can be seen in [51] where it shows the nonlinear behavior of exponential waveform before start to linear after a long time. The researchers also use different time fitting (100h, 200h, 300h, 400h, 500h and 600h) is done by implementing the non-linear least-square fitting to the data obtained by the experiment in order to gather the model parameters for 3 F Cooper Bussmann PowerStor SC. Shorter time fitting shows higher error compared to longer time fitting. Nevertheless, the proposed model of the simple fractional-order model is suitable to represent supercapacitor for the self-discharge behavior as its simulation can imitate the experiment result.

4. EXPERIMENTAL MEASUREMENT APPROACH

The experimental method for the self-discharge study gives real-life data based on the sample of SC used. It just used straightforward measurement to identified the self-discharge behavior and the characteristic of the supercapacitor when physically measuring the SC. It clearly able to shows the nonlinear waveform of the self-discharge of the SC. Direct measurement for self-discharge of supercapacitor does not need any complex circuit analysis or mathematical modelling. However, the equipment used must have high efficiency and it required an adequate setup to make sure the measurement is accurate.

From the experiment done in [52], the higher the rated voltage, the voltage drop at the early phase is also high. The terminal voltage measurement obtained from 6 units of MAXWELL 3000 F 2.7 V SC in series connection to accumulate 16.2 V terminal voltage value. Each waveform is recorded at every terminal of each supercapacitor starting from 2.7 V up to 16.2 V. Saha *et al*. [53], the results obtained by the experiment done shows that the lower capacitance value of supercapacitor shows higher leakage current throughout the self-discharge study compared to a higher capacitance value.

Another experimental study for self-discharge study was done in [21] where the researchers make a comparison study on effect of charging current level toward the charge redistribution. The MAXWELL 360 F supercapacitor has a higher self-discharge rate when charged by a 15A constant current source compared with the same supercapacitor but only a 1A constant current source is applied to the supercapacitor during charging. Leakage current in a supercapacitor is also caused by the thermal occurrence inside the supercapacitor during charge movement and the surrounding such as the environment temperature. The thermal energy caused the self-discharge rate to speed up due to the electrochemical reaction in the electrolyte of the supercapacitor. As in [54], the effect of temperature was applied to study the self-discharge behavior. At a higher temperature at 50 °C and 25 °C, the voltage drop is higher compared to when the supercapacitor is stored and the terminal voltage is measured at lower temperature conditions at -20 °C. The slow charge movement at low temperature due to low thermal energy caused the self-discharge rate to become low.

5. DISCUSSION

Different methods and approaches have been made to study and model the behavior of a supercapacitor. Each method used has its advantages and disadvantages throughout the studies. All the methods can show the self-discharge characteristic behavior either through modelling the supercapacitor or direct measurement from the supercapacitor itself. The high discharge rate during early moment of self-discharge or when the SC is disconnected from the source shows the nonlinear behavior of SC and its exponential waveform for the terminal voltage before linear over the time. Figure 2 shows the example of the self-discharge behavior of the SC based on three branch ECM study. Figure 6 and Figure 7 also shows the self-discharge characteristic done based on two branch ECM and Experimental method, respectively. Figure 7 shows that charging current greatly affected the self-discharge rate of the supercapacitor as discussed earlier. The proposed method also used different time frame to collect the result. The equivalent circuit model used shorter time to measure the self-discharge while the fractional order model used hundreds of hours of time fitting. This as the ECM used in the reviewed method are based on minimal number of branches which the error might increase due to its only containing a limited number of branch if the simulation is done and compared with the experiment if the time for measurement is taken for days [33]. Fractional order model might have more complex mathematical model with more complex computation. But it gave better estimation for a long time running. A comparison was made for all three (3) discussed an approach for the self-discharge behavior of supercapacitor in this paper and can be seen in Table 1.Table 1. Advantages and disadvantages of each method applied for Self-discharge studies

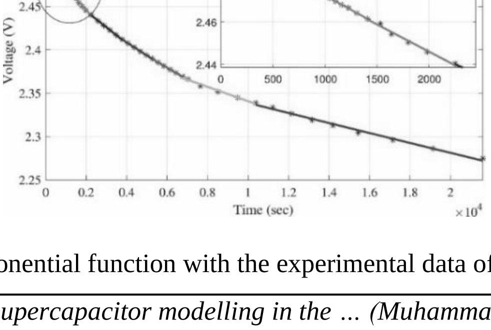

Figure 6. Comparison of exponential function with the experimental data of the 22 F supercapacitor [40]

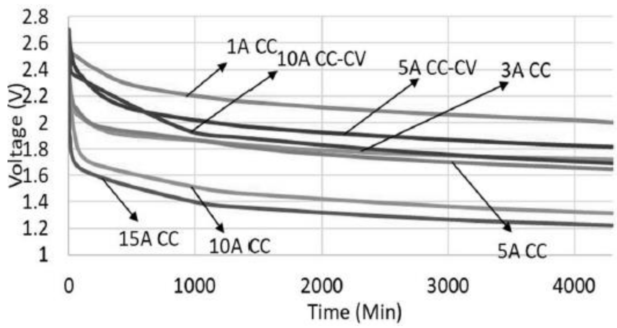

Figure 7. MAXWELL 360F supercapacitor self-discharge characteristic at different charging current [21]

Table 1. Advantages and disadvantages of each method applied for Self-discharge studies

Methods	Advantages	Disadvantages	References
Equivalent circuit model (three branch ECM and two branch ECM)	• Relatively easy to implement. • Use circuit analysis to identify parameters. • Three branch model is adapted in MATLAB Simulink for the Supercapacitor Block.	• Moderate accuracy (can improve the parameter identification with algorithm implementation). • Not suitable for longer time estimation as only limited to 2 or 3 RC branches. • A lot of parameters need to be identified.	[27], [29], [31], [33]–[35], [37], [38], [40], [43]
Fractional order model	• Some fractional-order model only needs 2 parameters. • Suitable for long time estimation. • More accurate data.	• Complex computation and calculation.	[45]–[47], [50], [51]
Physical measurement/ experiment	• Easy to implement; direct terminal voltage measurement. • Actual data; behavior can be studied directly from measured data. • Does not need complex parameter estimation.	• Costly; equipment setup to measure and monitored the supercapacitor terminal voltage might cost a lot and the cost of supercapacitor itself. • Longer time spend to measure and recorded the data.	[21], [52]–[54]

6. CONLUSION

This paper reviewed the model and method proposed by different researchers based on the equivalent circuit model, fractional order model and direct measurement approach for the self-discharge study of SC. Various method used and done to obtain the optimum and maximum accuracy towards the study. The parameter estimation is important for simulation study to increase the model accuracy. Hence, researchers come with different approach to optimize the parameter estimation. The simple model reviewed in this paper cannot be used directly for self-discharge behavior in term of physics study as it might not give perfect correlation. However, the method proposed is enough to make an estimation towards self-discharge behavior for different application. Various approach can be used on top of the circuit analysis method to identify the parameter. Those approaches were proposed to improve the accuracy of the supercapacitor behavior through the simulation model. Also, different manufacturer of SC might have different manufacturing process during the production of supercapacitor such as the type of electrode, size and thickness of electrode and the material used as electrolyte which then might affect the self-discharge behavior. Future study could adapt the proposed method and improved the parameter estimation for either ECM or fractional order model for better estimation accuracy and validate the supercapacitor from different manufacturer at the same capacitance value. The self-discharge study also played important part in energy management as it may affect the state-of-charge estimation which indirectly can lead to various unwanted condition for SC application. Hence, the important of self-discharge study of supercapacitor need to be considered when implementing the SC as energy storage.

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